Novel Acoustic Scattering Processes for Target Discrimination

Philip L. Marston
Physics Department, Washington State University, Pullman, WA 99164-2814
Phone: (509) 335-5343 Fax: (509) 335-7816 Email: marston@wsu.edu

Award Number: N000140410075
http://134.121.46.58/Research/acoustics.htm

LONG TERM GOALS

This is part of the Shallow-Water Autonomous Mine Sensing Initiative (SWAMSI) to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to examine issues supportive of the SWAMSI team effort by improving the understanding of acoustic scattering processes relevant to MCM and the shallow water environment. The current emphasis is on the interpretation of bistatic synthetic aperture sonar images. An example of another issue investigated at Washington State University is the scattering of sound by a plastic truncated cone. The cone material and shape were selected to be relevant to high frequency signatures of certain explosive-filled mines. Other objectives involved improved understanding and modeling of scattering mechanisms that are broader in scope and are outlined below.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different *amounts of time* to acquire the needed data for a given potential mine field. Consequently it appeared to Marston that the SWAMSI program should retain research components that support both *low frequency* and *high frequency* sonar technologies. It would be potentially useful to understand which features of the scattering are important for discriminating between live (explosive-filled) targets and decoy targets containing other materials. Commonly used explosives have some similarity to certain solid plastics in their acoustic properties: (1) both materials have longitudinal wave speeds greater than the speed of sound in sea water, but less than rocks, cement, or metals: (2) in many cases both materials have shear wave velocities *less than* the speed of sound in sea water.

The approach has several activities. Many of these were summarized in the annual report submitted in September 2005 [1]. The current report will emphasize the principal activities for FY2006. These activities were:

(1) *Improved apparatus for laboratory based acquisition of scattering data:* With the partial support of this grant and other ONR grants (N000140310583 and N000140310585) significant improvements were made to our 7000-gallon facility used to acquire monostatic and bistatic scattering data at Washington State University. The changes involve improved computer control of data acquisition as well as the ability to scan the position of a receiving hydrophone over a wide range of scattering angles. The list of activities noted below concern tasks primarily associated with grant

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE		3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Novel Acoustic Scattering Processes for Target Discrimination**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Washington State University,Physics Department,Pullman,WA,99164-2814**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

N000140410075. Other activities primarily associated with other grants are reported elsewhere. The principal graduate students participating in these modifications and in their subsequent testing are: C. Dudley, A. Espana, and K. Baik.

(2) *Bistatic short pulse scattering from metallic cylinders* (including the case of two cylinders): To facilitate the interpretation of scattering mechanisms, it is helpful to view the evolution of the time dependence of the echoes as a function of scattering angle.

(3) *Bistatic synthetic aperture sonar imaging* (based on acoustic holography algorithms): It has been possible to form images from data acquired as noted in item (2) by the application of a back-propagation algorithm based on the methods of acoustic holography. Selected results relevant to the interpretation of Bistatic SAS images are noted in this report. This algorithm was developed by the graduate student supported by this grant (K. Baik).

(4) *Bistatic SAS imaging using an alternative algorithm*: An alternative algorithm was developed by Dr. Steve Kargl at APL for applications such as the SAX-04 data [2]. Kargl's algorithm has an advantage over the holographic algorithm noted in (3) in that it is not necessary to assume bistatic samples are closely spaced. Dr. Kargl has kindly supplied a detailed description of his algorithm which Baik has modified for data acquired at WSU.

(5) *Scattering by a truncated cone:* In mathematical terminology a bluntly truncated cone is known as a frustum of a cone. In one target of interest, the explosive has this approximate shape. Our approach was to machine a frustum of a cone from a polystyrene-based material. The shape corresponded to the target of interest, but reduced in size so that scattering measurements could be carried out at scaled frequencies. The measurements were exploratory to determine if there were obvious high frequency signatures sensitive to the material properties of the target.

(6) *Truncated plastic cone modes* (modeling of modes using finite elements): A supplemental computational investigation of the acoustic response of a truncated plastic cone was carried out using finite element methods (FEM) based on a Fem-Lab/Comsol algorithm. The emphasis was on identifying the physical nature of the principal modes. Dr. David B. Thiessen assisted in the FEM calculations.

(7) *Scattering of Bessel beams by a sphere*: Relatively few exact analytical results are available for the scattering of acoustic beams by simple objects. With the partial support of this grant the scattering of sound was analyzed for a sphere centered on a Bessel beam. Additional information is noted in the report for grant N000140310583.

WORK COMPLETED

In addition to the progress outlined below in the Results section, the following completed items are noteworthy. Some results of Marston's earlier ONR-OAS funded research on caustics were published [3,4]. Related results were presented in invited talks [5,6]. The work noted in item (7) was submitted for publication [7].

RESULTS

The principal progress on the activities listed in the Approach section is summarized below:

(1) *Improved apparatus for laboratory based acquisition of scattering data:* Some results obtained using the improved system are noted below. Other results are noted in the report for grant N000140310583.

(2) *Bistatic short pulse scattering from metallic cylinders*: Figure 1 illustrates one of the geometric configurations investigated. Data was acquired for cylinders hung with their axis vertical. A hydrophone was scanned horizontally at the same depth as the cylinders. The source transducer, located as shown in Figure 1 was also placed at the same depth. The source was driven with a single-cycle 300 kHz tone burst. Data was acquired both with two cylinders present and with the cylinders hung separately. The larger diameter of the two cylinders (5.1 cm diameter) was a solid stainless steel cylinder which supports leaky Rayleigh waves in the frequency range of interest. The other cylinder (3.8 cm diameter) was an empty stainless steel shell which is known from prior experiments [8,9] to support leaky Lamb waves and related guided waves. One way to display the records is to plot the envelope of the signal record as a function of the hydrophone position. This is illustrated in Figure 2 for the case of two cylinders both present in the illuminated region. The earliest family of arcs is associated with the smaller of the two cylinders (the hollow cylinder). Those arcs contain information associated with the elastic response of the cylinder as well as the specular reflection from the outside of the cylinder. The second family of arcs (which is slightly tilted relative to the first family) appears to originate from the larger of the two cylinders. Finally, there is a distinct third family of arcs (which arrives later) that turns out to be associated with rays from the larger cylinder that subsequently interact with the smaller cylinder. Some of the arcs in the different families display an apparent intensity modulation that is the result of interference from weak superposed echoes from signals reflected from the top and bottom of the water tank. That interference does not affect the extracted images. While not shown here various details of the cylinder echoes have been calculated using ray-theoretic methods.

(3) *Bistatic synthetic aperture sonar imaging:* A method was developed for producing images from the time records recorded as explained above in (2). The basic idea is to back-propagate the sampled acoustic signal using algorithms originally developed for high-frequency acoustical holography [10]. Data is only acquired by scanning a hydrophone along a single line, but this is sufficient to provide cross-range resolution of the SAS image. Range resolution is provided by using a short tone burst to illuminate the targets and by constructing a time-evolving acoustic hologram such that the signal time relative to the arrival of the specular reflection is displayed. The relative time corresponds to an apparent relative range divided by the speed of sound. The recorded signals are processed in such a way as to use only the "supersonic" wave-number components. This was previously demonstrated by Hefner and Marston [10] to give useful information about the elastic response of targets. Figure 3 shows the resulting image where only the solid cylinder is present in the imaged region. The arrival time and cross range location of various features make it possible to identify image features with specific ray processes associated with the scattering. These include reflection from the cylinder and leaky Rayleigh wave propagation on the cylinder. (For a discussion of ray models, see for example [11,12].)

Figure 4 shows the SAS image generated when both cylinders were present. This corresponds to the geometry illustrated in Fig. 1 and the data shown in Fig. 2. The image of the large cylinder in Fig. 4 is on the right and has several features in common with Fig. 3 (for the isolated cylinder). The image of the smaller cylinder appears on the left in Figure 4 and it contains several features also present in an image of the isolated smaller target (not shown here.) Various features in the isolated case are also explained using ray theory [11,12]. Figure 4 also contains several features associated with the multiple scattering of sound pulses between the cylinders. The relevant rays are shown in the diagram on the

left. The cross range and arrival time of those features can be predicted approximately from ray theory. This comparison gives the feature identifications shown in Figure 4 on the left. A noteworthy aspect of Figure 4 is what we call the perspective effect in holographic bistatic SAS. Even though the hollow cylinder is more distant from the SAS array, the associated primary image on the lower left is earlier than the image solid cylinder on the right. This is because as shown in Figure 1, the smaller cylinder is closer to the sound source. This is also the reason why the hollow cylinder echo arrives first in Figure 2.

(4) *Bistatic SAS imaging using an alternative algorithm:* Images using an alternative algorithm (based on "time-domain imaging" [2]) show features in common with the holographic algorithm developed at WSU. The bistatic perspective distortion is reduced and in some cases images are easier to interpret. In other cases, the holographic images are easier. Baik has discovered how to transform from one perspective to the other.

(5) *Scattering by a truncated cone*: Higher resolution backscattering data is available than the data provided in the 2005 report [1]. The time dependence of the backscattering is displayed as a function of the tilt angle of the cone. Specific features have been identified that are associated either with external reflections or with rays transmitted through the cone in the form of longitudinal or shear waves.

(6) *Truncated plastic cone modes* (modeling of modes using finite elements): A large number of low-frequency modes were identified including vibrations with oscillating strains on the interior of the cone. In addition a series of modes were found associated with waves that circumnavigate the base of the cone. Some aspects of the scaling of those features could be estimated from elasticity theory for waves on a wedge. The features are only partially analogous to waves that have been observed to circumnavigate the edge of a circular plate. [13]

(7) *Scattering of Bessel beams by a sphere:* The partial wave analysis predicts a localized backscattering enhancement. The magnitude and angular width of that enhancement was confirmed and separately calculated using ray theory [7].

(8) *Other areas*: There has been progress [6]. Contact Marston if information is needed.

IMPACT/APPLICATIONS

Our laboratory based bistatic SAS observations are potentially useful for anticipating image features present in at-sea observations. This includes the perspective effect noted in the Results section. Our discovery of various non-specular scattering enhancements for a plastic truncated cone and other targets suggests that high-frequency acoustic signatures could be used to distinguish between certain explosive-filled and decoy mines, provided the acoustic information is *carefully selected*.

REFERENCES

[1] P. L. Marston, Annual report for grant N000140410075 (September 2005).

[2] S. G. Kargl, K. L. Williams, E. I. Thorsos, & J. L. Lopes, "Bistatic synthetic aperture sonar measurements and preliminary analysis," in *Boundary influences in high frequency, shallow water acoustics*, edited by N. G. Pace and Ph. Blondel (2005) p. 137-143.

[3] P. L. Marston, K. Baik, C. F. Osterhoudt, & A. L. Espana, "Ray methods and experiments for targets with and without boundary interactions," in *Boundary influences in high frequency, shallow water acoustics*, edited by N. G. Pace & Ph. Blondel (2005) p. 333-339.

[4] B. R. Dzikowicz & P. L. Marston, "Doubly-focused backscattering from finite targets in an Airy caustic formed by a curved reflecting surface," J. Acoust. Soc. Am. 118, 2811-2819 (2005).

[5] P. L. Marston, B. R. Dzikowicz, & A. L. España, "Diffraction catastrophes in acoustical scattering (invited)," 15th US National Congress on Theoretical and Applied Mechanics (Boulder, Co., June 2006).

[6] P. L. Marston, "Leaky wave excitation on concave surfaces and hyperbolic Fresnel zones (invited)," J. Acout. Soc. Am. 119, 3335 (A) (2006).

[7] P. L. Marston, "Scattering of a Bessel beam by a sphere," submitted to J. Acoust. Soc. Am.

[8] S. F. Morse, P. L. Marston, & G. Kaduchak, "High frequency backscattering enhancements by thick finite cylindrical shells in water at oblique incidence: experiments, interpretation and calculations," J. Acoust. Soc. Am. 103, 785-794 (1998)

[9] S. F. Morse & P. L. Marston, "Backscattering of transients by tilted truncated cylindrical shells: time-frequency identification of ray contributions from measurements," J. Acoust. Soc. Am. 111, 1289-1294 (2002).

[10] B. T. Hefner & P. L. Marston, "Backscattering enhancements associated with the excitation of symmetric Lamb waves on a circular plate: direct and holographic observations," Acoustics Research Letters Online 2 (1), 55-60 (2001) {http://ojps.aip.org/ARLO/top.html}.

[11] K. L. Williams & P. L. Marston, "Backscattering from an elastic sphere: Sommerfeld-Watson transformation and experimental confirmation," J. Acoust. Soc. Am. 78, 1093-1102 (1985).

[12] N. H. Sun & P. L. Marston, "Ray synthesis of leaky Lamb wave contributions to backscattering from thick cylindrical shells," J. Acoust. Soc. Am. 91, 1398-1402 (1992).

[13] B. T. Hefner & P. L. Marston, "Backscattering enhancements associated with antisymmetric Lamb waves confined to the edge of a circular plate: direct and holographic observations," Acoustics Research Letters Online 3 (3), 101-106 (2002); {http://ojps.aip.org/ARLO/top.html}.

PUBLICATIONS

B. R. Dzikowicz & P. L. Marston, "Doubly-focused backscattering from finite targets in an Airy caustic formed by a curved reflecting surface," J. Acoust. Soc. Am. 118, 2811-2819 (2005) [published, refereed].

P. L. Marston, K. Baik, C. F. Osterhoudt, & A. L. Espana, "Ray methods and experiments for targets with and without boundary interactions," in *Boundary influences in high frequency, shallow water acoustics*, ed. by N. G. Pace & Ph. Blondel (2005) p. 333-339 [published].

P. L. Marston, "Scattering of a Bessel beam by a sphere," [submitted].

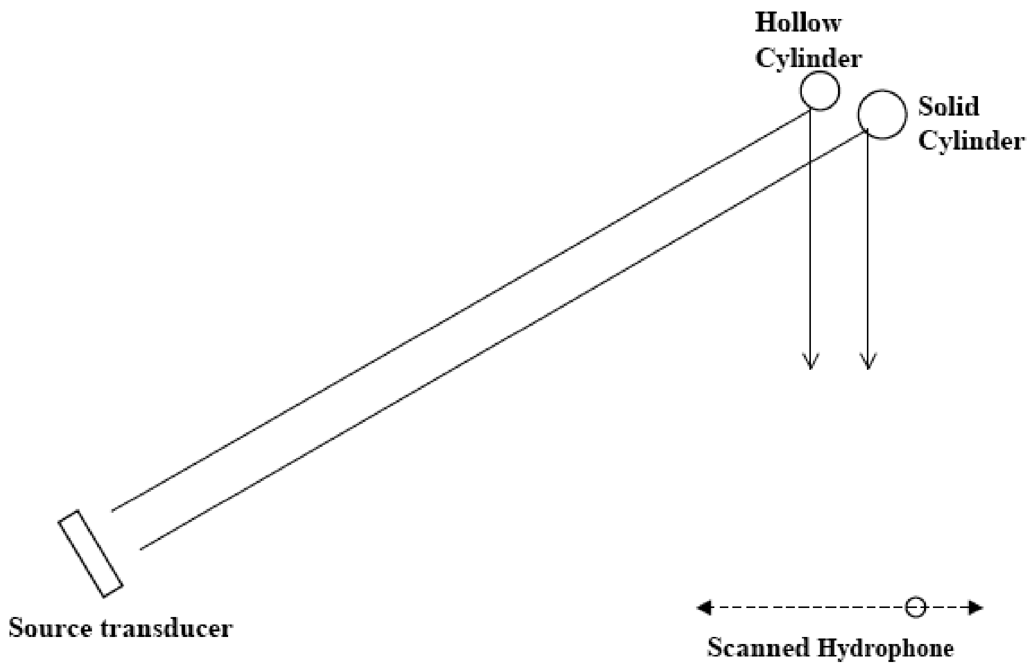

Figure 1. Example of the configuration used for laboratory-based bistatic scattering and synthetic aperture sonar measurements. The configuration is viewed from above. A wide-bandwidth sound-source (lower left) illuminates the target of interest (upper right). A hydrophone is scanned along a line in equally spaced increments to record the transient response of the targets. These measurements are used to display the angular evolution of transient echoes and they facilitate the construction of bistatic SAS images. Two cylinders are shown hung vertically. The solid cylinder is 90 cm from the scan-line and the hollow cylinder is more distant. For this situation, processed time records are shown in Figure 2 and a SAS image is shown in Figure 4.

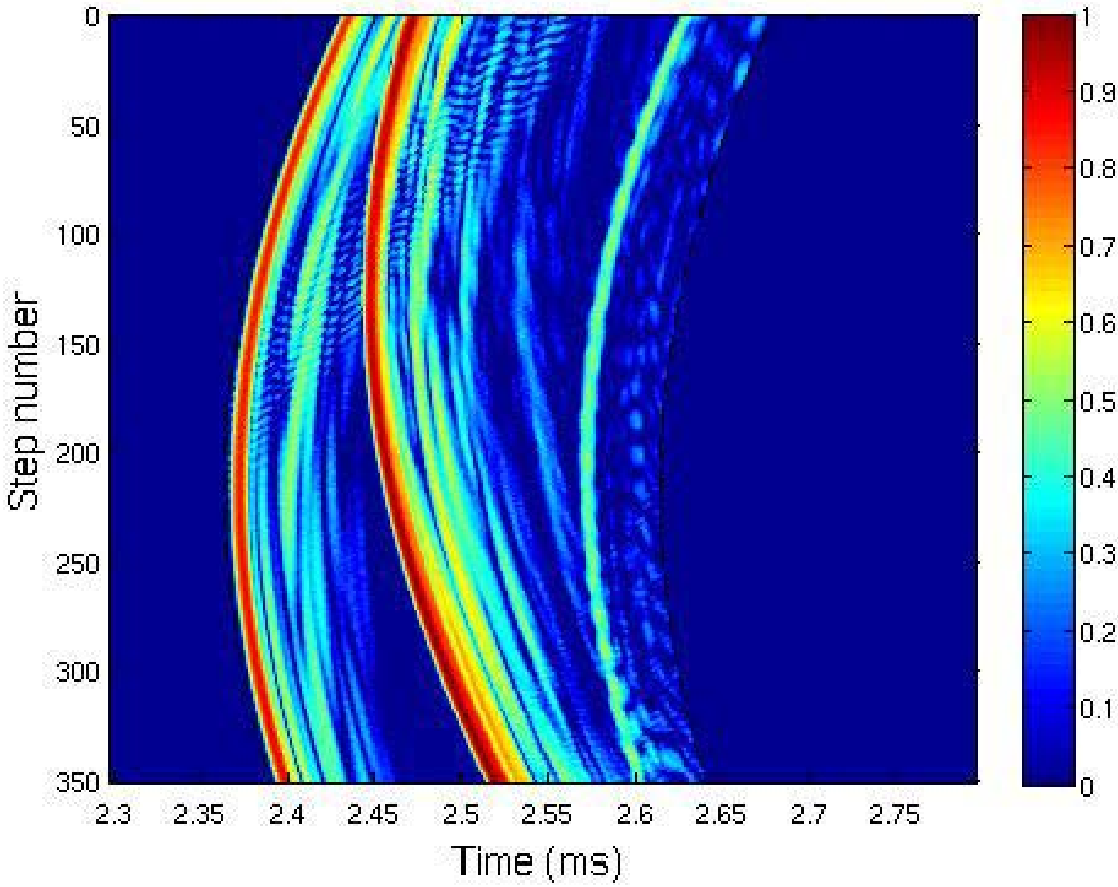

Figure 2. Example of the evolution of the envelope of the bistatic scattering for the configuration shown in Figure 1 in which there are two vertical cylinders illuminated by a transient incident wave. The incident wave is a short 300 kHz tone burst. The envelope of the received signal is extracted and signal level is plotted as a color. The horizontal axis is echo arrival time from 2.3 to 2.8 milliseconds. The vertical axis is the step number which is proportional to the hydrophone displacement. Step 0 corresponds to a hydrophone on the right side of Figure 1. Step 350 corresponds to a hydrophone displaced 70 cm to the left. The signal level is identified using the color bar on the right. The dynamic range is 35 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 35 db below the strongest signal. Families of arcs and some of the specific substructure can be identified with scattering processes using ray theory. Some superposed modulation is the result of weak superposed echoes from the top and bottom of the water tank.

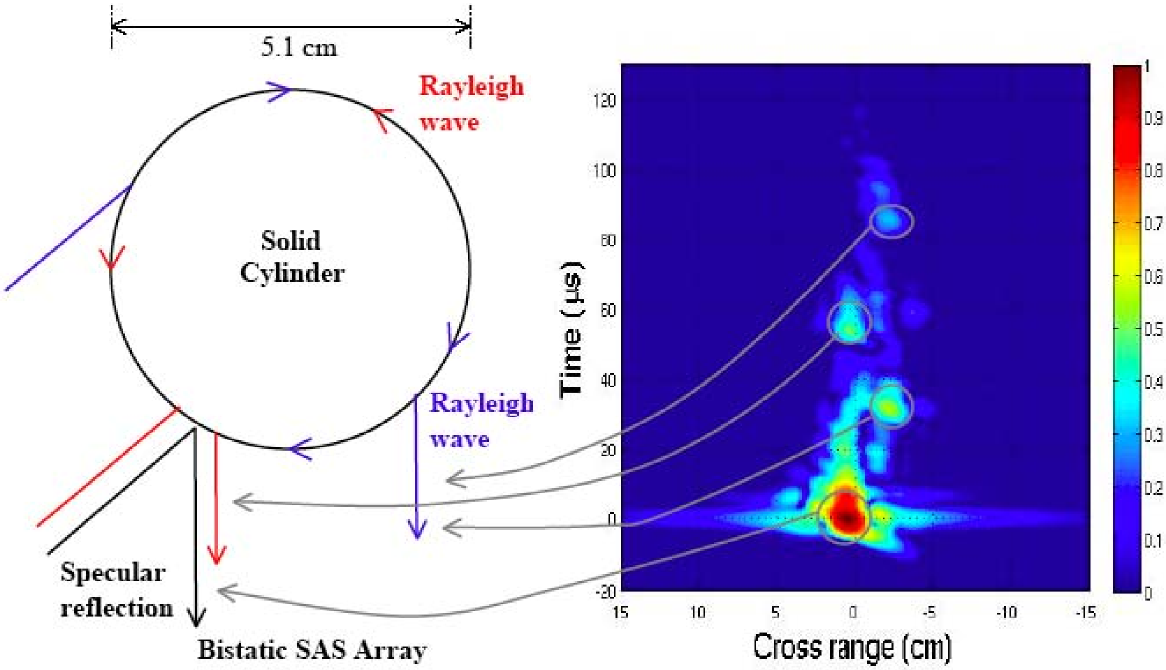

Figure 3. On the right side is a bistatic synthetic aperture sonar image of an isolated solid steel cylinder. The horizontal axis is the cross range at the imaged region. The vertical axis is the apparent range expressed in time relative to the arrival of the specular reflection. Increasing time corresponds to greater apparent range. The signal level is plotted as a color. The dynamic range is 40 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 40 db below the strongest signal. Some of the main features of the SAS image are identified in the ray diagram on the left. The ray shown in blue on the left is associated with a clockwise propagating leaky Rayleigh wave on the solid cylinder. The ray shown in red on the left is associated with a counter-clockwise propagating leaky Rayleigh wave on the solid cylinder. The diagram of the cylinder on the left is drawn with an expanded scale for clarity.

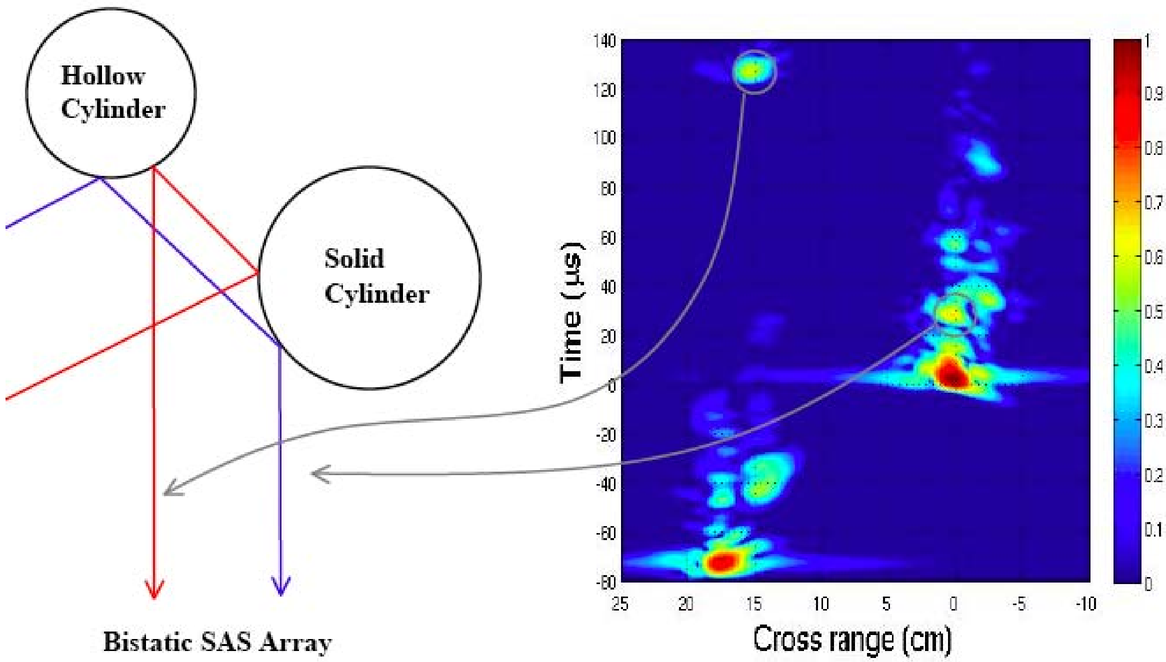

Figure 4. On the right side is a bistatic synthetic aperture sonar image with two cylinders present. As in Figure 3, the horizontal axis shows cross range and the vertical axis shows the apparent range expressed in time relative to the specular echo from the right-most cylinder which is a solid steel cylinder. The dynamic range is 40 db with dark red corresponding to the strongest signal and dark blue indicating a level at least 40 db below the strongest signal. The features on the lower left of the image are associated with the specular reflection from (and waves guided by) the hollow steel cylinder on the left side of the region viewed. That signal arrives prior to the first reflection from the cylinder on the right even though the cylinder on the right is closer to the SAS array. The reason is because the cylinder on the left is closer to the source. The diagram shown on the far left gives the ray diagram for specific features in the image caused by sound reflected first from one cylinder and then from the other cylinder. The cross-range and timing of those features are predicted by ray theory.